


Scalable real-time distributed DER control

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Project Objectives

▶ AC OPF Theory

- Math foundation for convex relaxation of OPF

▶ DER optimization algorithms

- Balanced mesh networks
- Unbalanced radial networks
- Centralized and distributed algorithms

▶ Modeling

- SCE distribution systems, feeders & secondary circuits

▶ Implementation & demo

▶ Tech-2-market



Project Objectives

► Uniqueness

- Guaranteed optimality and convergence
- New framework for algorithm design

► Challenges

- Mesh networks, unbalanced networks
- Distributed algorithms with guarantees (stab, perf)
- Numerical stability

► Performance metrics

- Distributed algorithm for unbalanced radial network
 - size (demo'ed): 2,000 buses
 - time: 5 mins
 - optimality gap: 5%



Algorithms scalable to 10K nodes and beyond

2014 accomplishments

- ▶ Convex relaxation of **unbalanced** network
- ▶ **Distributed** relaxation algorithms
- ▶ Distribution system **modeling**
- ▶ **Implementation** & demo



2014 accomplishments

► Convex relaxation for **unbalanced** network

— Theory

- Chordal relaxation (exploits sparsity)
- Branch flow model, bus injection model

— Algorithms

- Extension of semidefinite algorithms to unbalanced radial networks
- Centralized and decentralized algorithms

— Simulations

- Centralized alg: SCE 2,000-bus, 3 mins, 0% gap
- Distributed alg: IEEE 123-bus, 3 mins, 0% gap





Simulation results (Aug 2014 review)

	Simulation performance	Target performance
#instances (4 week)	8,064	8,064
#instances solved (convergence)	100%	80%
suboptimality gap (exactness)	0%	5%
solution time (per instance)	2 min	3 mins

- Uses generalized BFM chordal relaxation using Rossi (~2000-bus) feeder
- Much more numerically stable than BIM
- Ran on 16 servers
- Exactness (ev ratios): 16.6M ratios (= 2064 lines/instance x 8064 instances)

2014 accomplishments

► **Distributed** relaxation algorithms

- Theory and algorithms: build on
 - Convex relaxation of OPF
 - Branch flow model
 - ADMM
- Simulations
 - Balanced radial network: 2,000 buses, 3 mins, 0% optimality gap
 - Unbalanced radial network: ~100 buses, <4 mins, 0% optimality gap





Computation time

Network size N	Diameter r _D	Iterations	Total Time	Avg time T
2,065 buses	64 links	1,114	1,153 sec	0.56 sec
1,313	54	671	471	0.36
792	53	524	226	0.29
363	36	289	66	0.18
108	16	267	16	0.14

- Suboptimality gap : 0%
- Compute time in distributed execution

Scalability trend

Regression: $T = 9.8 \times 10^{-7} N + 8.6 \times 10^{-3} D$



Comparison: ADMM-based algs

Huge speedup

- Recent distributed OPF algorithms (inc ours) are **ADMM-based**
- All these algorithms solve the ADMM subproblems in each update **iteratively**
- Ours solves them in **closed form**

per-bus computation time	x-update	z-update
Our algorithm	1.7×10^{-4} sec	5.1×10^{-4} sec
CVX	2×10^{-1} sec	3×10^{-1} sec
speedup	1,176x	588x

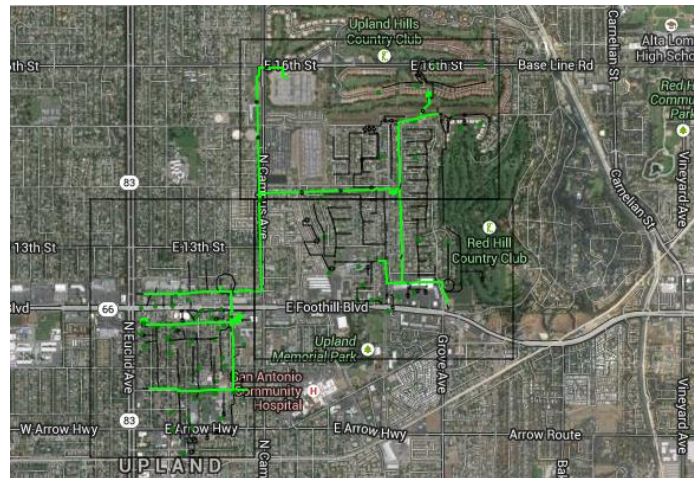
per-bus computation time : time to solve 1 sample ADMM iteration for Rossi circuit with 2,065 buses, divided by 2,065, for both algorithms

2014 accomplishments

► Distribution system modeling

— SCE systems

- 6 feeders (4KV, 12KV)
- ~15,000 buses
- <10% error compared with substation measurements

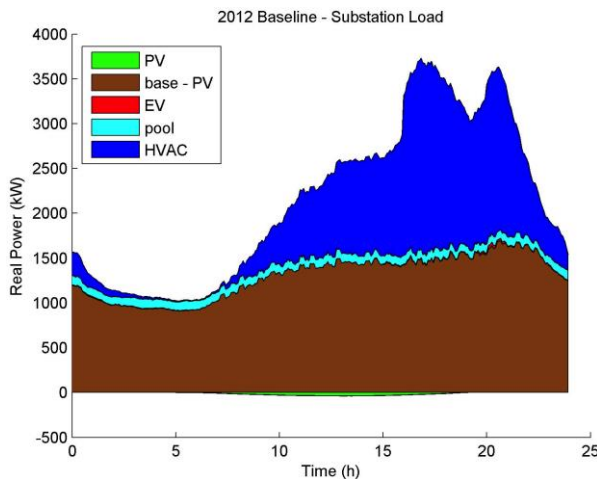


2014 accomplishments

► Implementation & demo

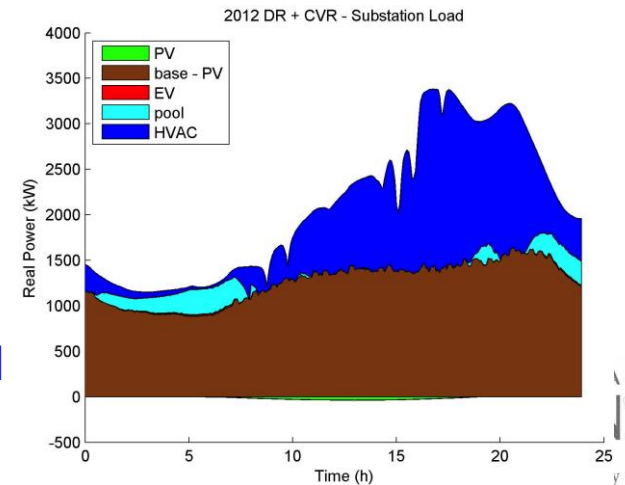
— SCE Rossi feeder

- ~2,000 buses
- DER: inverters, HVAC, EV, pool pumps
- Unbalanced multiphase
- 4-week simulations



peak load reduction: 8%
energy cost reduction: 4%

baseline

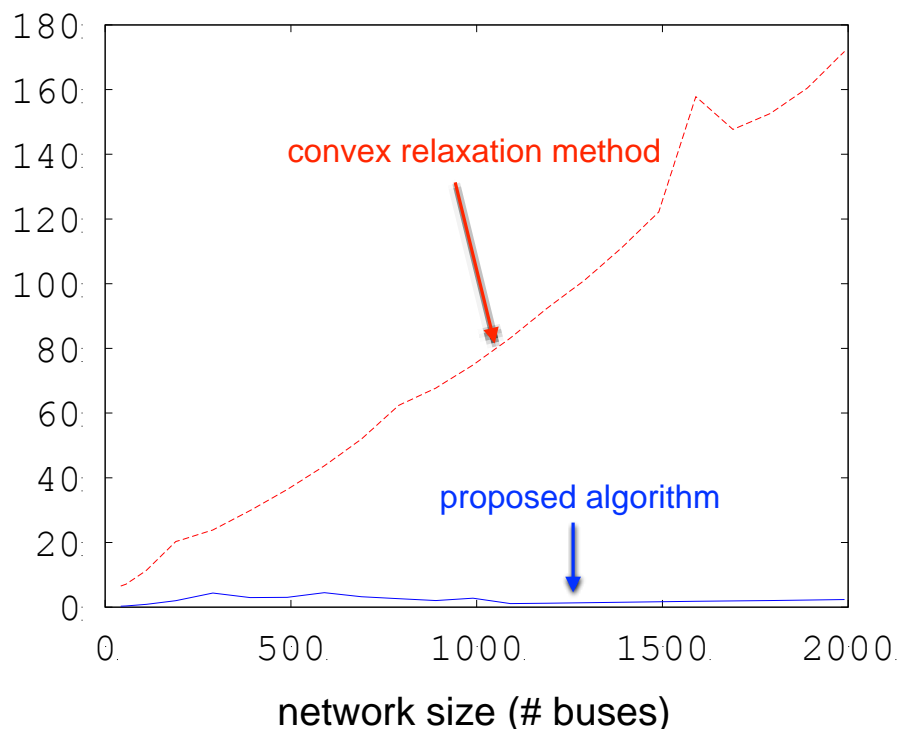


optimized

Remaining tasks

► Distributed OPF for unbalanced network

- SCE Rossi feeder: ~2,000 buses
- time: 5 mins
- optimality gap: 5%



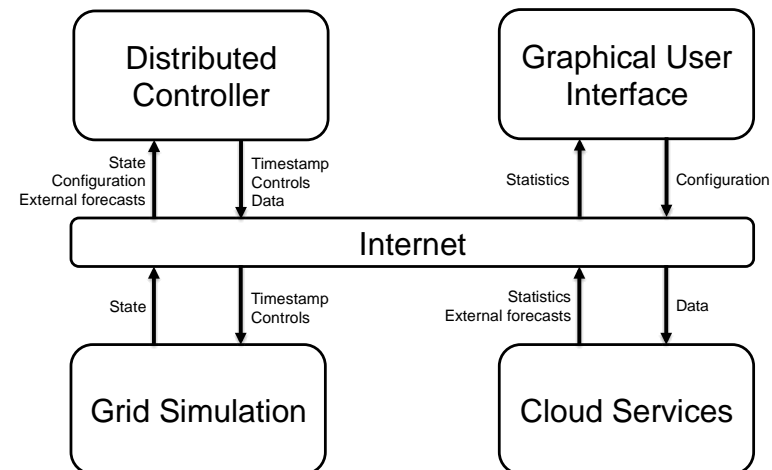
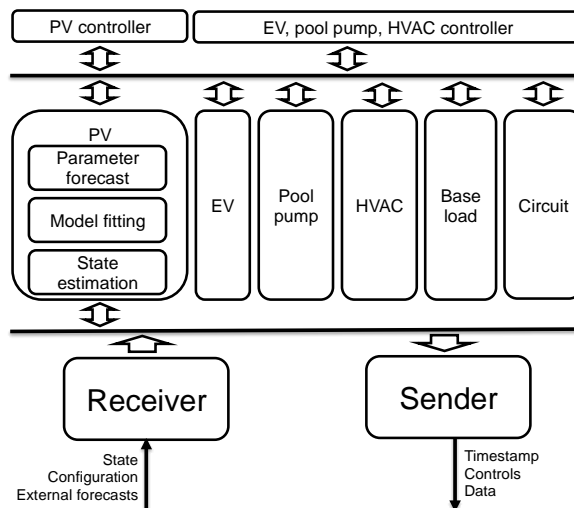
Tech-to-market

► T2M objectives

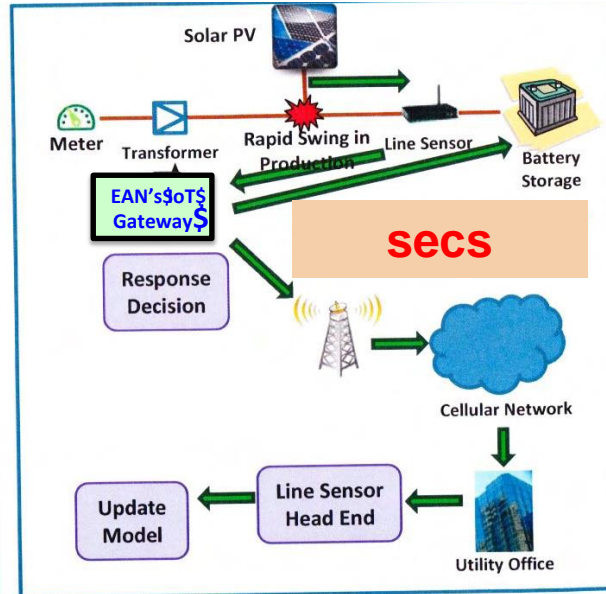
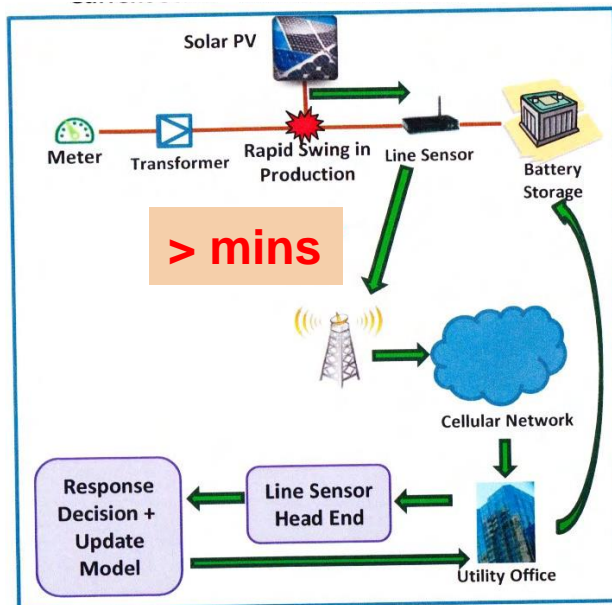
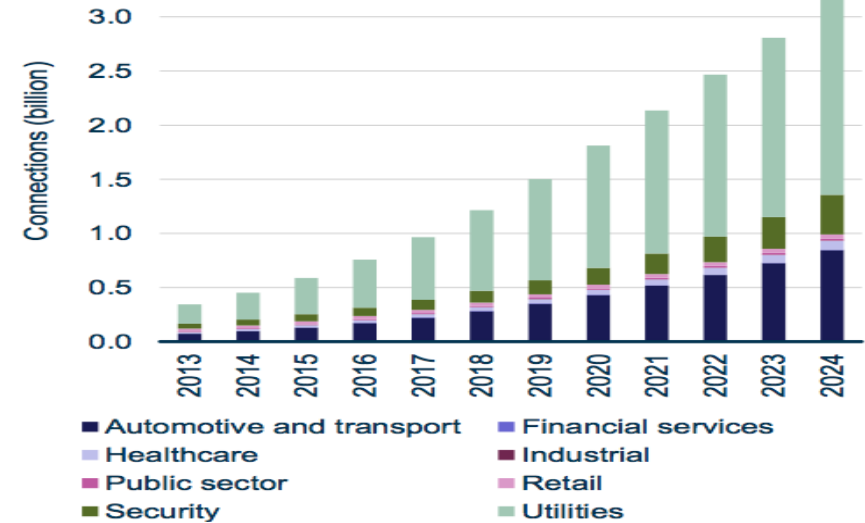
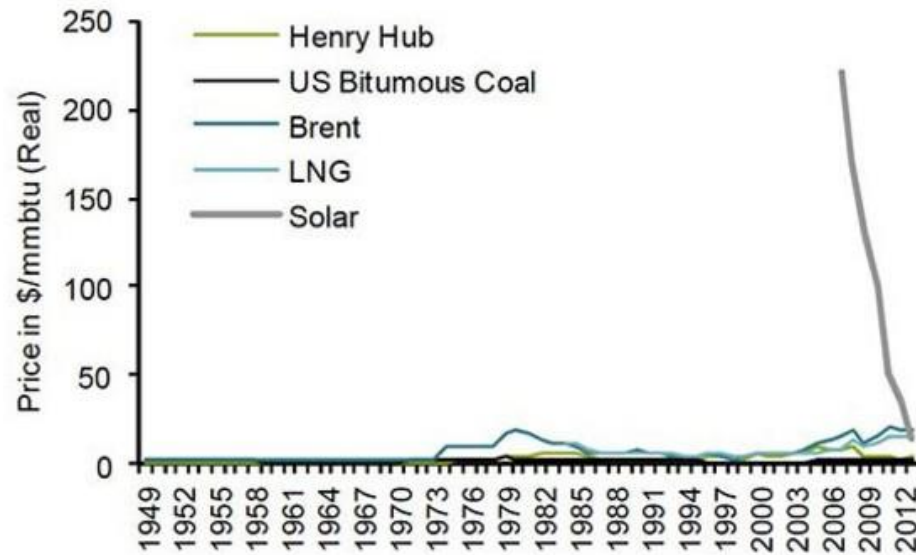
- Validation: market, technology

► Key activities

- IAB, Berkeley Haas C2M project
- Prototype
- Pilots, VC and strategic investments



Tech-to-market



Post ARPA-E goals

► New R&D

- Builds on existing results for fast timescale dynamic control & optimization
- Scalable distributed real-time control with guaranteed stability and performance

► Implementation & pilots

- Commercial grade software for DERMS
- Pilots with industry

► Tech-to-market



Conclusions

► Most important contributions

- Math foundation for convex relaxation of OPF
- Relaxation algorithms: unbalanced radial, distributed
- Detailed feeder models
- Implementation & demo

► Challenges

- Numerical instability, scalability
- Data for realistic and detailed models
- T2M: prototype, pilots



Backup slides



DERMS applications

control

$$u(t) = \underset{u}{\operatorname{argmin}} \operatorname{OPF}(u; \hat{x}(t))$$

estimate
& learn

$$\hat{x} = \hat{f}(\hat{x}(t), u(t); e(t))$$

$$\hat{y} = \hat{g}(\hat{x}(t), u(t))$$

$$e(t) = y(t) - \hat{y}(t)$$

CIS

GIS

data

$y(t)$

$u(t)$

GridLab-D simulator

$$\dot{x} = f(x(t), u(t))$$

$$y = g(x(t), u(t))$$

estimate state
in fast timescale